DESTRUCTIVE EVALUATION AND EXTENDED FATIGUE TESTING OF RETIRED AIRCRAFT FUSELAGE STRUCTURE

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Abstract

In this study, the Federal Aviation Administration (FAA) and Delta Air Lines are teaming to conduct a destructive evaluation and extended fatigue test of a retired aircraft. The objective of this research is to develop a knowledge base within the FAA and the broader aviation community on the experimental procedures, analytical methods, and data reduction approaches for a destructive evaluation and extended fatigue test of retired aircraft. The knowledge gained will be useful in assessing programs to preclude widespread fatigue damage (WFD).

This paper summarizes the planned activities for the destructive evaluation and extended fatigue test of a retired passenger aircraft. The 3-year effort involves the destructive evaluation, inspection, and testing of sections removed from a retired aircraft at or near its design service goal. The sections removed will be representative of fuselage structure susceptible to WFD. The primary focus will be to characterize the state of multiple-site damage (MSD) and multiple-element damage in fuselage structure using detailed nondestructive inspection (NDI) and destructive examination. The state of MSD will be advanced through extended fatigue testing using the FAA's Full-Scale Aircraft Structural Test Evaluation and Research facility and then assessed through NDI and destructive evaluation. The extended fatigue testing will provide data to enable calibration and validation of prediction methodologies and will serve as a test bed to evaluate the sensitivity and effectiveness of standard and emerging inspection technologies to detect small cracks. The data generated from this effort will be used to calibrate and validate WFD assessment methods.

Introduction

In performing structural evaluations and assessment for continued airworthiness of high-time operational aircraft, comprehensive teardown inspections have been and are routinely conducted in both the commercial and military sectors. Information and data developed from destructive evaluation and extended fatigue testing have been instrumental in ensuring structural integrity of aircraft, especially those nearing their design service goal (DSG). Teardown inspection activities are essential to evaluate airframe structure susceptible to widespread fatigue damage (WFD). Section 25.571 of Title 14 Code of Federal Regulations, as revised by amendment 96, requires that it "be demonstrated with sufficient full-scale test evidence that widespread fatigue damage will not occur within the design service goal of the airplane." Corresponding Advisory Circular, AC 25.571-1C, provides general guidelines on the requirements of the demonstrated sufficient full-scale fatigue test evidence. The AC recommends rigorous posttest teardown inspections as a way to generate sufficient evidence. Because of the lack of test results and technical data, AC 25.571-1C does not specify the teardown protocol, inspection procedures, data collection, and subsequent analyses.

While the expertise and knowledge base to conduct teardown inspections are well established by the large commercial airframe original equipment manufacturers (OEM) and military sectors, comprehensive guidelines and data that are documented and available to the broader aviation community are lacking. In the civil arena, this information is proprietary and is disclosed only to the Federal Aviation Administration (FAA) who must rely on the OEM for interpretation of the data. For teardown activities sponsored by the military, generic information on visual and nondestructive inspections (NDI) can be obtained. However, this information is not documented, not generally available for public dissemination, and has limited application to commercial aircraft. Military aircraft are less frequently used compared to commercial aircraft. As such, military aircraft are typically in service longer and have more corrosion-related problems compared to commercial aircraft. While fatigue cracking is a concern for the military fleet, corrosion damage is a major economic life-limiting factor. Fatigue cracking is predominately the life-limiting factor for commercial aircraft.

In addition, service examples demonstrate the practical need for additional research on the development of multiple-site damage (MSD) in fuselage lap joints [1]. Much of the experimental and analytical research of MSD during the past decade has focused on lap joint upper skin cracking (e.g., Aloha 1988). However, beginning in December 1998, MSD cracks were found in the lap splice lower skin, lower fastener rows of B727 aircraft. After disassembly, a 20-inch crack spanning an entire bay was discovered as shown in Figure 1. In 1999, Airworthiness Directive (AD) 99-04-22 was issued to

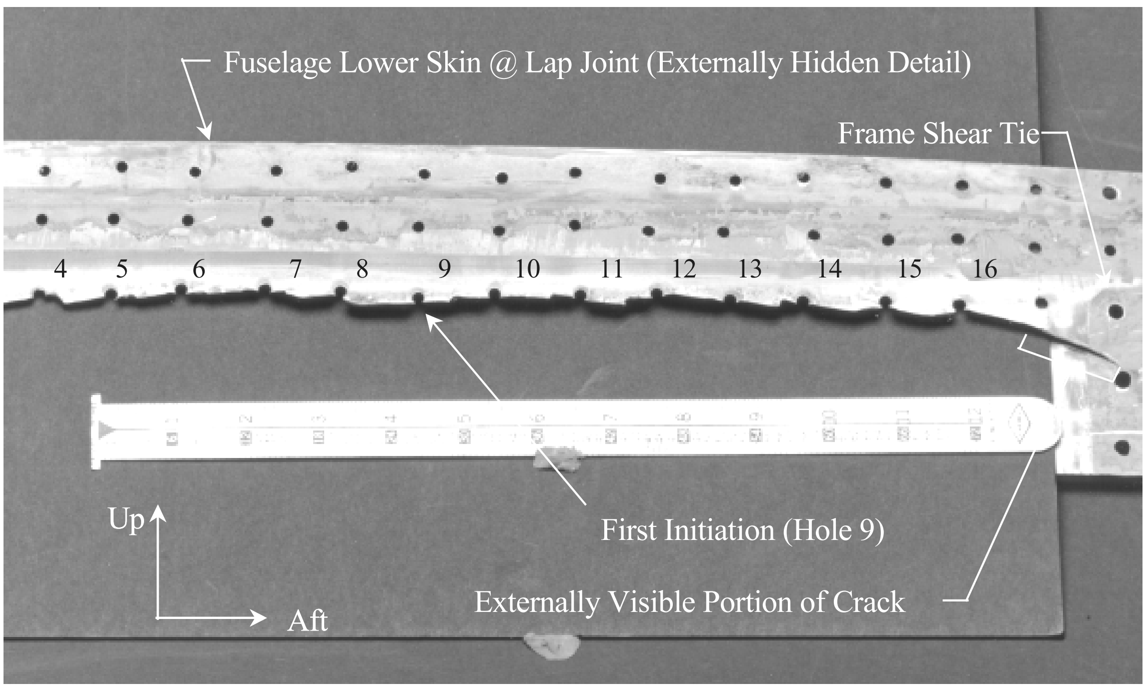


Figure 1. Crack discovered in lap joint of B727 [1]

mandate inspections of the lap joints deemed most susceptible (i.e., fuselage skin lap joints with inherent-induced bending stresses due to eccentricities caused by differing outer and lower skin thickness and 100% reliance on fasteners for load transfer). This type of cracking is distinct from those commonly investigated in the past and raises new technical issues concerning detectability, panel bulging, large crack arrest, and the influence of initiation factors such as fastener fit and fretting in the joint.

Also in 1999, the Airworthiness Assurance Working Group (AAWG) published technical recommendations on rulemaking to prevent WFD in the commercial fleet [2]. The AAWG rule-writing group, as tasked by the FAA, is currently using those recommendations in developing programs to preclude the occurrence of WFD. The concept of using a monitoring period to manage WFD was introduced based on a final damage condition that conservatively satisfies regulatory strength requirements. Typically, a final damage condition is selected such that there is a small risk of a single MSD linkup in any aircraft during operation.

The destructive testing and analysis of structure removed from retired aircraft can provide the FAA with first-hand knowledge of teardown procedures that may be conducted in support of applications for continued airworthiness certification. Experience and knowledge gained from this destructive analysis will enable the FAA to issue essential rules, policy, and advisory circulars pertaining to the prevention of WFD. Extended fatigue and residual strength testing of sections of actual fleet aircraft will result in data that will enable calibration and validation of prediction methodologies and can serve as a test bed to evaluate the sensitivity and effectiveness of standard and emerging inspection technologies to detect small cracks.

General Technical Tasks

The research involves the destructive evaluation, inspection, and testing of nine lap-spliced panels removed from a retired narrow-body airplane at or near its DSG. The sections removed will be representative of fuselage structure susceptible to WFD identified in reference 2. The primary focus will be to characterize the state of MSD in the fuselage structure using detailed NDI and destructive examination. The state of MSD will be advanced through extended fatigue testing using the FAA's Full-Scale Aircraft Structural Test Evaluation and Research (FASTER) facility and then assessed through NDI and destructive evaluation.

Description of Airplane

A Boeing 727-232 airplane with serial number 20751 and line number 1000 was selected for this program. A typical B727 airplane is shown for example in Figure 2. It is a Federal Aviation Regulation (FAR) Part 25 certified aircraft representative of typical FAR Part 121 revenue-service passenger aircraft currently in the domestic fleet. The airplane was placed into service in 1974 and retired in 1998. During that time, the airplane accumulated 59,497 flight cycles and 66,434 flight hours and is near its DSG. The airplane was owned and operated exclusively by Delta Air Lines, has been well maintained and stored, and has a well-documented and accessible service history. In addition, the airplane was retired prior to AD 99-04-22; thus, no inspections and repairs were made per this AD. A prerequisite for the aircraft chosen is that the entire usage in terms of flight types, mix, and hours are known. Thus, this aircraft is ideal for this study for obtaining in-service conditions.

Figure 2. Typical B727 as selected for program

Sections Removed

At least nine fuselage lap joint areas susceptible to WFD, each approximately 8 by 12 ft, will be inspected, removed from the aircraft, shipped, and prepared for destructive evaluation and extended fatigue testing. Figure 3 shows the approximate location of the nine sections that will be removed from the aircraft. The fuselage lap joint areas were selected to match those called out in AD 99-04-22. The lap joint in these areas consists of 0.063-inch 2024-T3 outer skins, lapped over 0.040-inch lower skins, and fastened by three rows of BACR15CE-6D rivets (similar to NAS1097-D6 rivets). Eight of the fuselage lap joint areas are located on the crown of the fuselage along the lap joint at stringer S-4R and S-4L between frame stations (FS) 360 and FS 720 and between FS 1009 and FS 1183. In this area, a floating frame construction is used with bonded tear straps at the frames as illustrated in Figure 4a. Tear straps are designed to force longitudinal cracks to turn circumferentially and flap, preventing the failure from progressing to adjacent bays. MSD cracking was found in these areas during fleetwide inspections subsequent to AD 99-04-22, thus it is anticipated that the sections will have MSD.

One large area located in the bilge of the fuselage along stringer S26L between FS 360 and FS 720 will also be examined in this study. In this area, a shear-tied frame construction without tear straps is used, see Figure 4b. This is the area where inner-layer cracking was first observed in this model aircraft, as reported in reference 1 and shown in Figure 1. Based on in-service experience, it is anticipated that cracks will be found in this area of the selected aircraft.

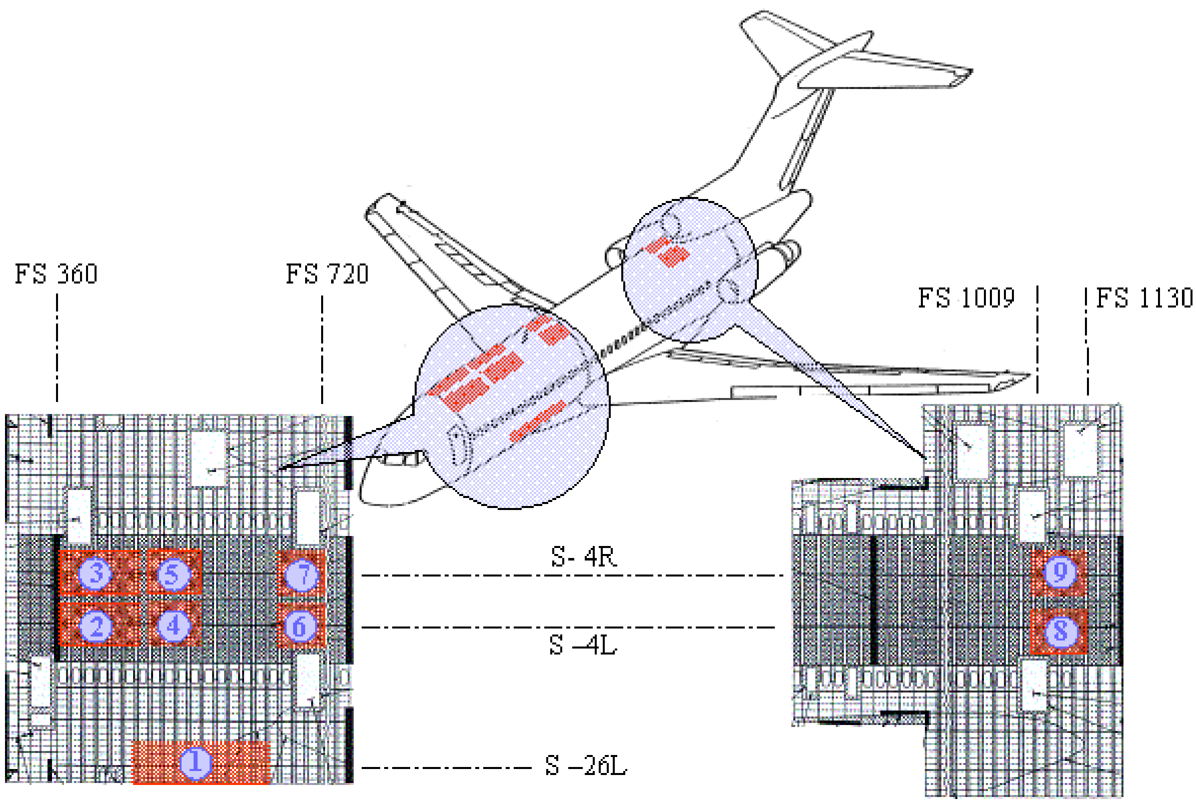
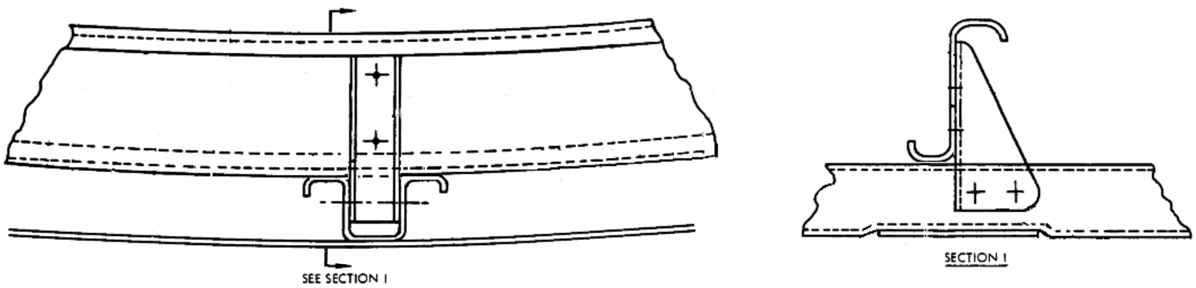
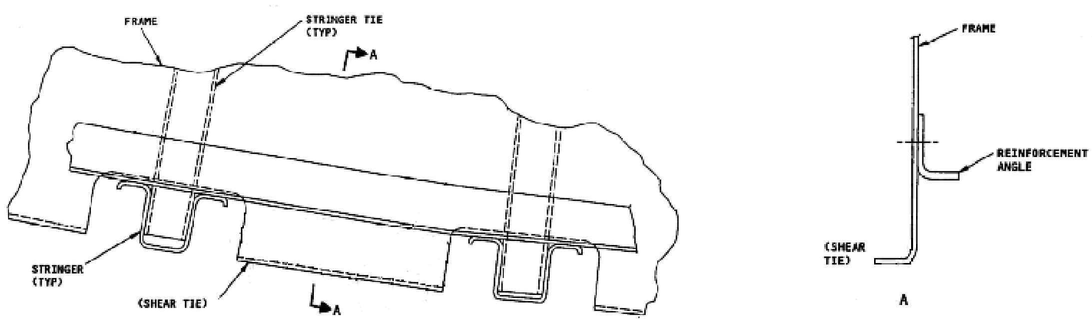


Figure 3. Sections removed



a. Floating Frame Crown Region along S4L and S4R



b. Shear-Tied Frame in Bilge Region Along S26L

Figure 4. Frame configuration

Inspection Capabilities

As part of this research, NDI technologies and visual inspection will be used to catalog and fully document the condition of the selected areas. Prior to removal, all sections will be labeled with boundaries and identification marks to indicate the location and orientation of the section with respect to the aircraft. Both visual inspection and NDI for cracks, corrosion, and tear strap disbonds of the selected structure will be done using procedures based on the OEMs recommended standard practice and directed inspection requirements (service bulletins or airworthiness directives). NDI data will be collected so that the signal response data can be analyzed later. Both conventional and emerging NDI technologies will be assessed to determine their field capability to detect small cracks. Second layer fatigue crack detectability will be baselined with mid- or low-frequency sliding probe eddy-current inspection techniques and compared with emerging inspection technologies such as magneto optic imaging (MOI).

Extended Fatigue Testing

Four fuselage panels removed from the selected aircraft will be tested at the FASTER facility. The FASTER test fixture, located and operated at the FAA William J. Hughes Technical Center shown in Figure 5, was established to assess the structural integrity of aircraft fuselage structure. A full explanation of this unique test capability can be found in reference 3. Briefly, the FASTER test fixture is capable of applying realistic flight load conditions to large sections of a fuselage structure. Both quasi-static and long-term durability spectrum loadings can be applied, including differential pressure, longitudinal, hoop and shear load in the skin, and hoop load in the frames. The system was designed using commercial-off-the-shelf components and to operate in an environment requiring minimal infrastructure support. Safety was considered in the design of the system by using water as the loading media. A simple loading mechanism consisting of levers, fulcrums, and water actuators, are used to economically introduce complex mechanical loading. This simplified mechanical design concept, in conjunction with a computer control and data acquisition system, presents a test system that is user-friendly, has low-cost maintenance, is inherently safe, and is highly versatile.

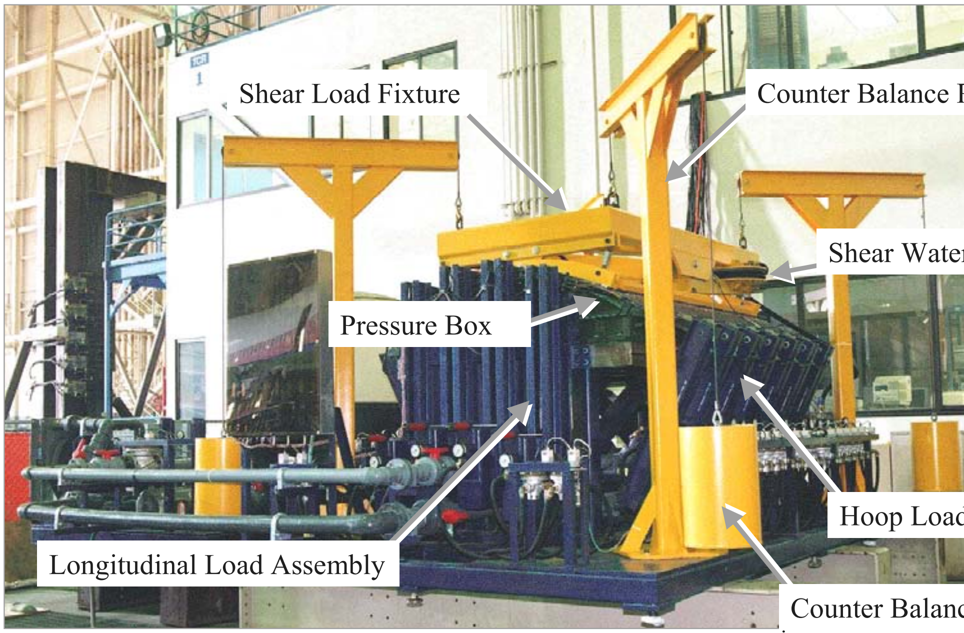


Figure 5. Full-Scale Aircraft Structural Test Evaluation and Research (FASTER) test fixture

The objectives of the extended testing are to (1) propagate and extrapolate the state of damage beyond one DSG; (2) characterize and document the state of damage through real-time NDI, high-magnification visual measurements, and posttest destructive evaluation of fracture surfaces; and (3) correlate analysis methods to determine crack initiation and detection, first linkup, and residual strength. To distinguish between cracks from extended fatigue testing and from service conditions, an underload marker band spectrum will be applied prior to fatigue testing.

Damage Characterization

Samples will be prepared for fracture surface examinations using high-resolution microscope and scanning electron microscope to characterize the state of damage. An example of such fracture surface characterization is shown in Figure 6. The extent of fatigue cracking, corrosion, faying surface fretting fatigue, and structural disbanding will be quantified through fractographic examinations. Select fastener holes will be split open to reveal the crack surfaces, and fractographic examinations will be performed to identify, catalog, and document crack initiation sites and mechanisms, crack shapes and sizes, and quality of the fastener hole surface. In addition, the crack growth histories will be empirically reconstructed using striation counts. Crack growth will be backed out to determine equivalent initial flaw size (EIFS) for later analysis validation.

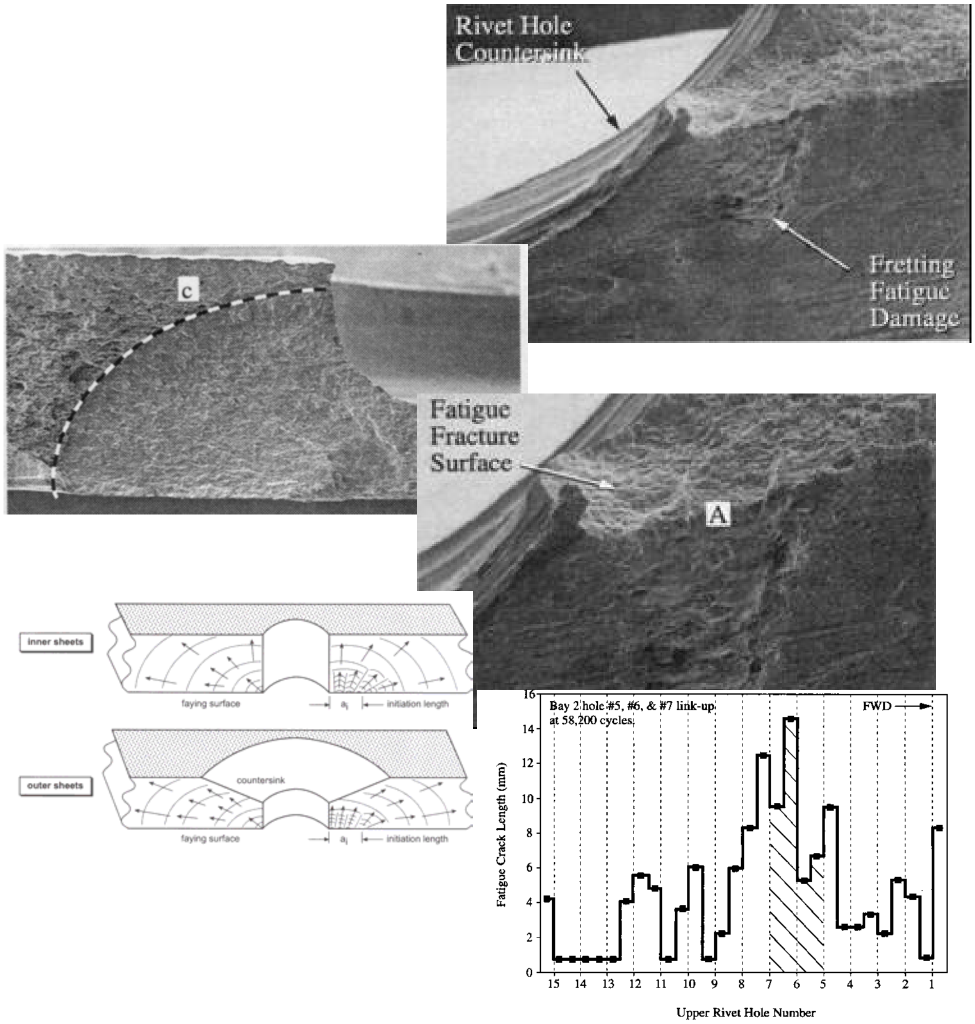


Figure 6. Figures from references 4 and 5 shown as an example of types of data that will be acquired in this project

Data Analysis

The crack data (patterns, distributions, sizes, and shapes) generated will be analyzed and used to characterize MSD crack initiation, crack detection, crack linkup, residual strength, and the WFD average behavior in the structures removed. Analysis methods will be developed to correlate the state of MSD at any point in time. The following analysis steps will be undertaken, as illustrated in Figure 7:

1. Generate Stress Spectra: A procedure to generate stress spectra representative of prior operation and usage for each structure removed will be developed. The basic aircraft usage (e.g., flight types, flight mix, and flight hours actually flown) will be used in generating the spectra.

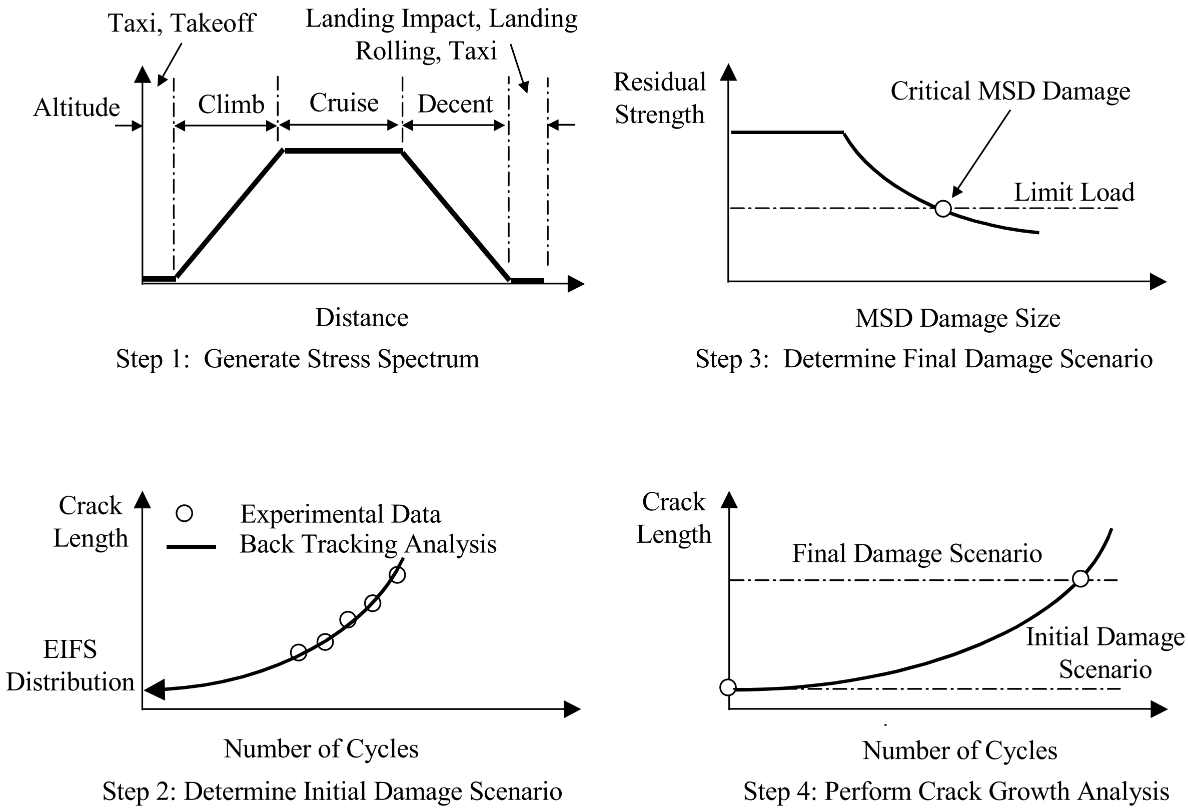


Figure 7. Schematic of analysis procedure

2. Crack Initiation and Initial Damage Scenario: A procedure will be determined to estimate the number of cycles to crack initiation and to estimate the size, extent, and distribution of cracks characterizing MSD initiation. Several methods will be investigated, including traditional empirical methods using extensive S-N test data with scatter factors, fracture mechanics-based EIFS concepts, and a relatively new fatigue initiation model for lap joints, Eijkhout Model, outlined in the National Aerospace Laboratory, report NLR-CR-2001-256 [4]. Using test data in a probabilistic analysis framework to determine crack initiation will also be investigated.

3. Residual Strength and Final Damage Scenario: The size, extent, and distribution of MSD that reduces the residual strength below predefined levels for the structure removed will be determined. Several approaches will be considered to estimate the final damage scenario, including engineering estimates using subcritical conditions and more rigorous techniques based on advanced elastic-plastic fracture criteria such as the critical crack tip opening angle and T*-integral [6].

4. Conduct Crack Growth Analysis: Fatigue crack growth analysis will be conducted from the initial damage scenario to the final damage scenario. Calculations will include the number of cycles to crack detection, to crack linkup, and to the final damage scenario. Government-funded or other publicly available codes and methods will be used. Standard linear elastic fracture mechanics models or advanced crack closure-based fatigue crack growth models will be considered. All methods considered will be assessed to determine the applicability and feasibility in conducting WFD assessments.

Significance and Output

The experience and knowledge gained from this project will enable the FAA to issue essential rules, policy, and advisory circulars pertaining to the prevention of WFD. Extended fatigue and residual strength testing of sections of actual fleet aircraft will provide data that will enable calibration and validation of prediction methodologies and will aid in evaluating the sensitivity and effectiveness of standard and emerging inspection technologies to detect small cracks.

The final output from this project will include documentation and a database containing, but not limited to the following:

- Rational for selection of the aircraft and structure analyzed
- Procedures and data from field and preteardown inspections
- Procedures used to remove structure from the aircraft
- Procedures and approach used in the extended fatigue cycling and residual strength test using the FASTER facility
- Data and results of all inspections, including delivery of signal response data in the form of an electronic database
- Data characterizing the state of damage including:
  - Fatigue crack distributions, locations, shapes, and sizes
  - Damage initiation mechanisms and locations
  - Reconstructed fatigue crack growth histories
- Quantification of corrosion, disbonds, fretting damage at faying surfaces, and other damage
- Descriptions of the crack growth analysis methodologies used
- Results of application of the methodologies as a means to analyze crack growth
- Results of application of the methodologies as a means to predict crack growth
- Description of the methods used to determine the MSD initiation, crack detection, and crack linkup
- Results of the analysis to determine MSD initiation, crack detection, and crack linkup
- Procedure and data from material characterization
- Conclusions and recommendations specific to determination of MSD initiation, crack detection, and crack linkup

Summary

This paper summarizes the planned activities for a 3-year project involving the destructive evaluation and extended fatigue test of a retired passenger aircraft near its design service goal (DSG). The sections removed will be representative of fuselage structure susceptible to widespread fatigue damage (WFD) defined by the Airworthiness Assurance Working Group (AAWG). The primary focus will be to characterize the state of multiple-site damage (MSD) in fuselage structure using detailed nondestructive inspection (NDI) and destructive examination. The state of MSD will be advanced through extended fatigue testing using the FAA's Full-Scale Aircraft Structural Test Evaluation and Research (FASTER) facility and then assessed through NDI and destructive evaluation. The extended

fatigue testing will provide data to calibrate and validate prediction methodologies and will aid in evaluating the sensitivity and effectiveness of standard and emerging inspection technologies to detect small cracks. The data generated from this effort will be used to calibrate and validate WFD assessment methods with data obtained from the analysis of real structure with natural fatigue crack initiation and accumulation of other environmental and accidental damage-induced small flaws that are representative of commercial transport use over an extended period of time (20-30 years).

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